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Seasonal variation of Nitrogen dioxide and particulate matter in the capital City (City of Tshwane) of South Africa and its compliance to South African Air Quality Standards

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Abstract

Air pollution is a major issue in metropolitan areas, including the City of Tshwane in South Africa. With a growing urban population and increased vehicles on the road, the air quality in the city has become a concern. This study aims to assess air quality compliance in the City of Tshwane Metropolitan Municipality by analysing the levels of PM_{10} and NO_2, two commonly monitored pollutants. The study obtained data from the SAAQIS database for the period from 2016 to 2020. The data was collected from network stations for ambient air monitoring within the city. The assessment of PM_{10} and NO_2 concentrations was conducted according to the South African National Ambient Air Quality Standards (NAAQS). The objectives of the study were to investigate the variations in NO_2 and PM_{10} levels across different seasons, evaluate the air quality within the city, and analyse the geographical patterns of these pollutants. The data analysis was performed using Microsoft Excel and SPSS techniques, while bar graphs and box and whisker plots were used to illustrate the results. The results of the study revealed that the City of Tshwane failed to comply with the NAAQS in terms of the recorded annual levels of NO_2 and PM_{10} at the Booysens neighbourhood. The levels of these pollutants exceeded the recommended standards, indicating a risk of being declared a hotspot within the city. The findings suggest that human-induced activities, such as biomass burning and coal-powered power plants, significantly contribute to the emission of PM_{10} and NO_2. The impact of these activities on pollutant levels is further exacerbated by prevailing weather conditions, particularly in residential zones during winter. In conclusion, this study highlights the urgent need to address air pollution in the City of Tshwane. The findings provide valuable insights into the sources and patterns of air pollution in the city, which can inform policy and decision-making to improve air quality and protect public health.

Keywords: Air quality compliance, Air pollution, Air quality assessment, Seasonal variation

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1. INTRODUCTION

Air pollution refers to chemicals or other pollutants that are either not ordinarily present in the air or in amounts that are detrimental to human health (Sharma et al., 2013). It primarily contributes to environmental effects such as acid rain (caused mainly by nitrogen and sulphur oxides in the atmosphere) (Ashfaq and Sharma, 2013). In addition, it can be caused by a vast number of emission sources, both natural and artificial (Sajjadi et al., 2018).

The fact that some of these substances enter the atmosphere directly from their origins gives rise to the term "primary pollution". They frequently include sulphur dioxide, nitrogen oxides, carbon monoxide, lead, organic compounds, and particle matter (Sari et al., 2019; Tian et al., 2015; Fortin et al., 2005; Schwela, 2000). Additionally, air pollutants are produced by various sources, including industry and traffic, and are influenced by socioeconomic variables (Sari et al., 2019; Tian et al., 2015; Fortin et al., 2005; Schwela, 2000).

Tian et al. (2019) found that urban land use patterns are closely related to air pollution. Land use distribution and shape impact air quality through spatial distribution and human activities (Wei et al., 2014). Previous studies (Misra et al., 2001; de Kok et al., 2006; Nyanganyura et al., 2007; Dionisio et al., 2010; Venter et al., 2012; Naidja et al., 2018) found that air pollution in Africa is caused by industry, transportation, home and commercial burning of living organisms, bush fires, live vegetation, sea spray, re-suspended dust from unpaved roads, and inadequate waste management.

Air pollution disrupts the economy (Tian et al., 2019). It causes adverse health effects such as respiratory infections (Wei et al., 2014), heart disorders (Hassan et al., 2015), autoimmune disorders, lung cancer (Bereitschaft et al., 2013), and damages the ecosystem (both the atmosphere and the soil) (WHO, 2014; Yang et al., 2014).

The country's economy is also energy- and carbon-intensive (OECD, 2013). Coal is an essential fuel for industrial activities in South Africa, and coal-fired power plants account for a significant portion of its consumption. The National Electricity Regulator (2000) says that 91 per cent of the power made in South Africa comes from coal. Even though the majority of power plants in South Africa burn low-grade coal, the resulting emissions of carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM) have produced significant environmental and health concerns for communities located near industrial "hot spots" (Spalding-Fecher, 2003). Pollution levels in South Africa are often high and harmful to people's health (Spalding-Fecher, 2003). This is especially true in large industrial areas like the South Durban Industrial Basin and the Vaal Triangle (Terblanche, 1994).

Furthermore, Mathee and Von Schirnding (2003) indicated that most of the problems related to air pollution in South Africa are caused by increased industrialization, poor land-use planning, rapid urbanization, and poverty. Hence, it has been demonstrated that poor land-use planning led to the co-location of substantial industrial development and densely inhabited residential areas (WHO, 1996; Barnard, 1999). Formerly disadvantaged demographic groups predominantly populate residential neighbourhoods next to industrial projects, most of whom are low socioeconomic level (Scott et al., 2005). Even though some of these regions may have access to amenities such as power, clean water, and transportation, they still have to cope with environmental issues (such as air pollution and noise pollution) that can negatively impact their health and well-being.

Air pollution in metropolitan areas is a big problem, particularly in developed and developing nations. Furthermore, in cities, it has been exacerbated by a growing urban population and increased vehicles on the road (WHO, 2014). Current estimates place more than 55% of the global population in urban areas by 2050, which is expected to climb to over 70% (United Nations, 2012). This phenomenon contributes to numerous public health problems, and South Africa is not exempt from this reality (Yang et al., 2014).

Furthermore, to this extent, studies have shown that air pollution is a substantial risk to humans and health and has been linked to increased illness and mortality (WHO, 2016). Similarly, the World Health Organization (WHO) says that particulate matter, and nitrogen dioxide (NO_2) form part of the pollutants of concern with severe environmental health risks (WHO, 2016).

Some of these pollutants' elevated exposure levels have been discovered in regions classified as hot spots or priority areas, demonstrating that South Africa's air pollution concerns are far from being remedied, especially in urban areas (SAAQIS, 2009; DEA, 2013).

Therefore, against this background, the City of Tshwane, one of the big agglomerations and the capital city of South Africa, is not exempt from issues related to poor air quality exposure. For instance, SO_2 and hydrogen sulphide (H_2S) odours have been detected in some regions of the City of Tshwane (Ngobeni, 2021). As a result, this is a source of concern for the populations that live in the affected areas and people who commute into the city. Thus, assessing air quality compliance in the City of Tshwane Metropolitan Municipality is urgent. The aim of this study is to provide the monitoring data for the levels of particulate matter (PM_{10}) and nitrogen dioxide (NO_2) in the City of Tshwane municipal region. Moreover, the objective is to assess and establish a starting point for future investigations on the atmospheric air quality in the Tshwane Municipal area, specifically focusing on the health impacts related to elevated levels of PM and NO_2 that exceed the guidelines set by the World Health Organisation.

1.1 ***Materials and methods***

Study area (shown in Figure 1)

The figure shows the air quality monitoring stations located in the Gauteng Province, the City of Tshwane (CoT) is the administrative capital of South Africa and serves as the country's financial and commercial hub.

Located in the Gauteng Province, the City of Tshwane (CoT) is the administrative capital of South Africa and serves as the country's financial and commercial hub. It is the biggest of the three metropolitan regions in the province, with a land area of 6 345 km^2, making it the third-largest city in the world in terms of land mass. It is the largest of the three metropolitan regions in the province (CoT IDP, 2014). Tshwane has an average yearly rainfall of around 670 mm. Summer (December to February – DJF) has the most rain, whereas winters (July to August – JJA) are pretty dry. The rainy season typically begins in October and ends in April. Summers are hot, with an average temperature of around 22 degrees Celsius, while winters are pleasant, with an average temperature of approximately 12 degrees Celsius. Washington and Todd (1999) say that the days are sunny, the skies are clear, and the nights are cool, though the lowest temperatures may sometimes drop below freezing.

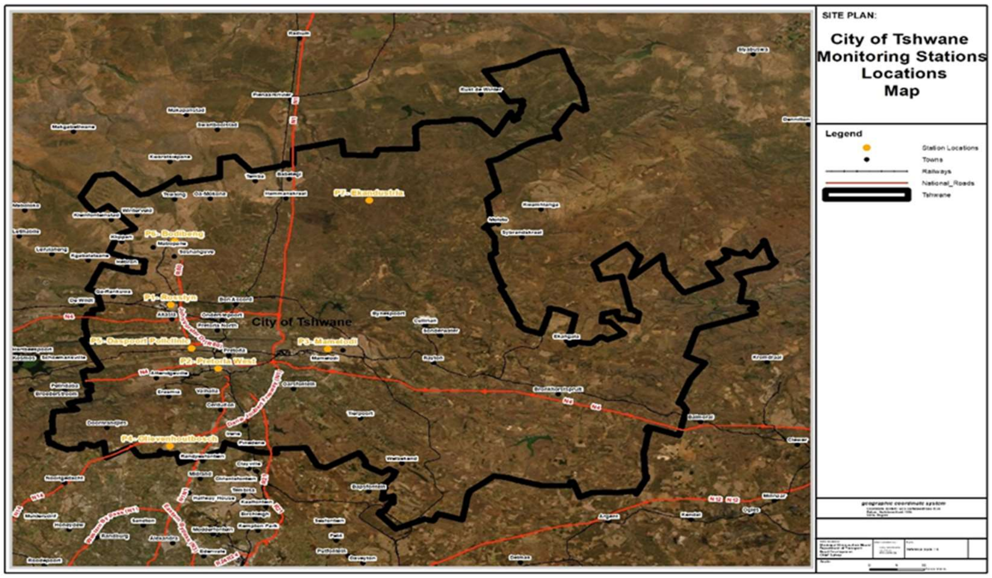

Figure 1. Location of the study area

1.1.1 Data collection

The assessment of NO_2 and PM_{10} concentrations, as well as the variability of pollutants, was carried out with the assistance of secondary air quality data for all of the monitoring stations in the City of Tshwane. These data were obtained from the South African Air Quality Information Systems and covered the period from 2016 to 2020 for NO_2 and PM_{10} concentrations. In order to determine the average concentrations, the data was computed using Microsoft Excel. On the basis of graphs and tables, a comparison was made between the average concentrations of NO_2 and PM_{10} that were measured at each station in the research area. Therefore, in order to ascertain the seasonal variation in concentrations of NO_2 and PM_{10} a whisker box plot will be created using Microsoft Excel for both the summer and winter seasons. The bar graphs and tables that were developed will be utilised in order to carry out the comparison of the NO_2 and PM_{10} concentrations that are present in the City of Tshwane Metropolitan Municipality.

The nature of the research that was carried out was quantitative, and this is because the goal of the study was to analyse the combined levels of three pollutants (NO_2, and PM_{10}) concerning the long-term annual limit values specified by the National Air Quality Standards, and also observed at the seasonal and spatial variations of pollutants. Secondary data on air quality for Nitrogen dioxide, Particulate matter and Sulphur dioxide from SAAQS are used for the present study from 2016 to 2020.

1.1.2 Statistical analysis

The data was succinctly presented through the utilization of descriptive statistics, such as the mean, standard deviation, and percentages, to enhance comprehensibility. Moreover, the annual trends of the pollutants in the study area were unveiled as a consequence of this investigation. The data was analysed using statistical tools, namely Microsoft Excel and SPSS 27.0. To evaluate alterations in air quality indicators, the researchers employed descriptive statistics and t-tests. Ultimately, the pollutant concentrations obtained from the monitoring locations were assessed in relation to South Africa's National Ambient Air Quality Standards (NAAQS) to determine compliance with the overall air quality restrictions of the city and the NAAQS.

1.1.3 Results and discussion

Spatiotemporal exposure levels of NO_2

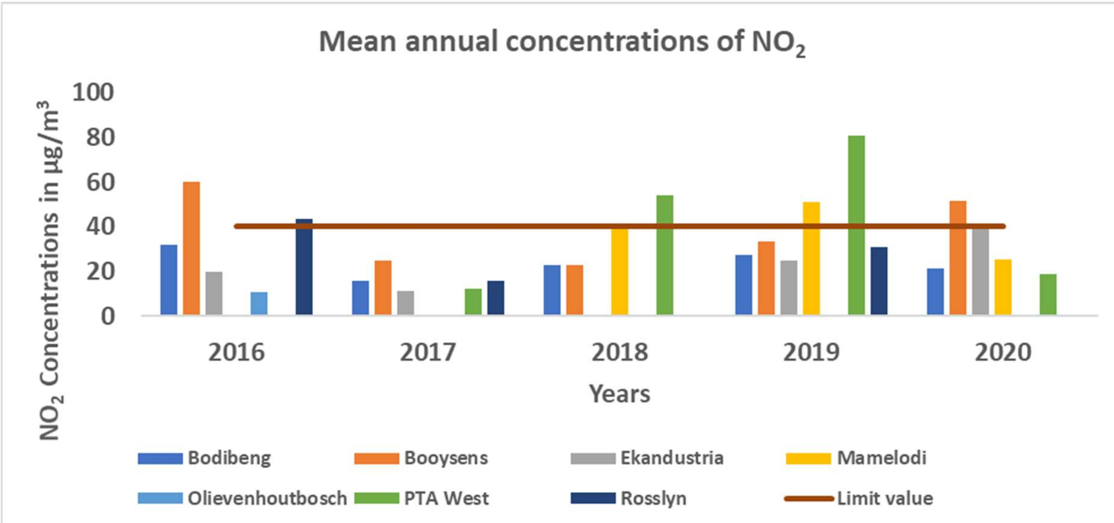

Figure 2: Mean annual concentrations of NO_2 in the City of Tshwane study areas from 2016 and 2020.

The results depicted Figure 2 provides a visual representation of the various levels of NO_2 concentration observed at the designated air quality monitoring stations located within the City of Tshwane Metropolitan Municipality. The results presented in the figure spans the period from 2016 to 2020. In the year 2016, the monitoring station located in Booysens observed increased concentrations of NO_2, with values reaching roughly 60.03 g/m^3 as shown in Figure 2. According to figure 2, in the same year, Rosslyn also had high concentrations, with levels reaching 43.35 g/m^3. Furthermore, it was observed that Mamelodi exhibited a concentration of 39.17 g/m^3, whereas Pretoria West had a value of 54.05 g/m^3, indicating increased levels of NO_2 in the year 2018. Furthermore, in the year 2019, Mamelodi and Pretoria West, had heightened levels of NO_2 concentrations, measuring at 50.9 g/m^3 and 80.75 g/m^3, respectively. In the year 2020, Booysens exhibited a measurement of 51.37 g/m^3 for increased levels of pollutants, while Ekandustria recorded a measurement of 39.79 g/m^3. Regions typified by industrial zones, including Rosslyn, Pretoria West, Mamelodi, and Booysens, have elevated levels of NO_2 as described in previous studies. As a result, emissions from industrial activities make a substantial contribution to the rise in concentrations of NO_2 exposure. The present study has resemblance to the analysis carried out in Abidjan, Côte d'Ivoire, wherein heightened concentrations of NO_2 were seen at three distinct industrial locations (Bahino et al., 2018).

Consistent data loss was observed at the following stations: Olievenhoutbosch in 2017, 2018, 2019, and 2020; Mamelodi in 2016 and 2017; Rosslyn in 2018 and 2020; and Pretoria West in 2016. This phenomenon is associated to dysfunctional monitoring stations, as highlighted by Madonsela (2019), Madonsela et al. (2023), and Ndletyana et al. (2023).

Spatiotemporal exposure levels of PM_{10}

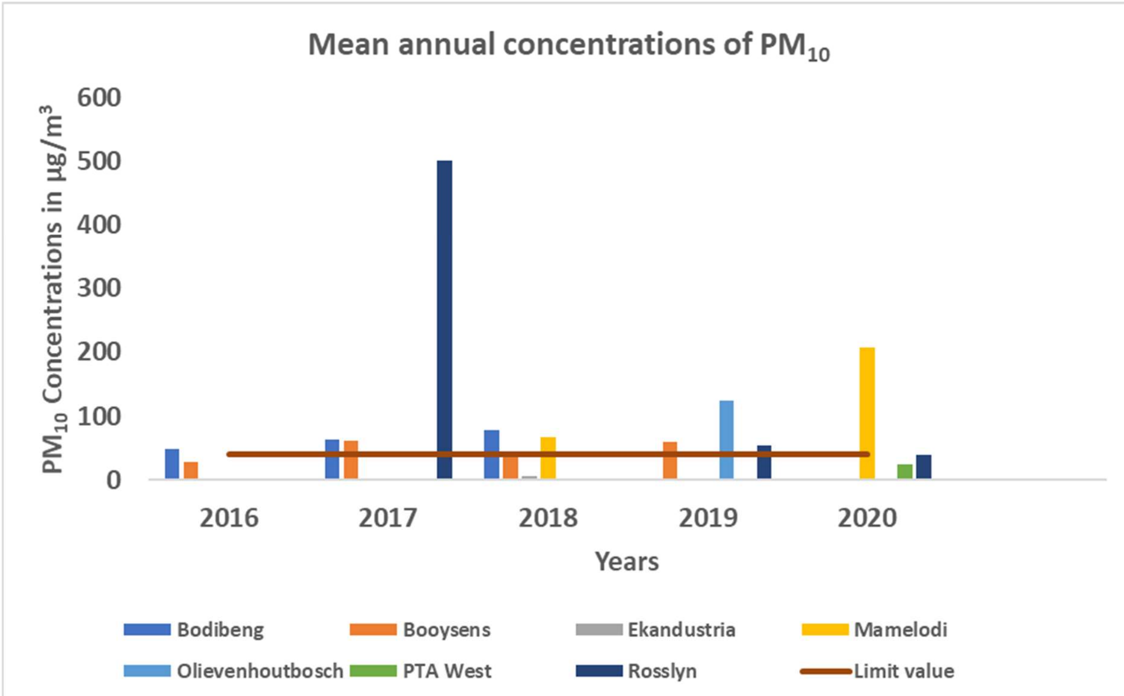

Figure 3: Mean annual concentration of PM_{10} from 2016 to 2020.

By considering the geographical characteristics of air pollution inside urban areas, a more comprehensive understanding of the overall impact of air pollution on cities may potentially be attained. In addition, it is important to provide assistance in identifying the origins of urban air pollution and formulating policies that are efficacious in mitigating the impacts of air pollution. Based on the information shown in Figure 3, it is evident that Bodibeng exhibited notably elevated levels of PM_{10} concentrations, with recorded values peaking at 49.21 g/m^3 throughout the year 2016. Moreover, much higher concentrations were observed in the Bodibeng region, reaching a measurement of 62.55 g/m^3 in the year 2017 as indicated in figure 3. In a similar vein, it was determined that Booysens exhibited elevated levels of PM_{10} particulate matter, measuring at 61.99 g/m^3 throughout the year 2017. Moreover, it is worth noting that Rosslyn saw abnormally elevated concentrations of PM_{10} particulate matter in the year 2017, with recorded values peaking at 500.58 g/m^3. Whereas, it is worth noting that Bodibeng had a substantial rise in PM_{10} concentrations, with levels peaking at 78.18 g/m^3 in the year 2018. In a similar vein, it is noteworthy that Booysens had an elevation in PM_{10} levels, wherein the concentrations escalated to 36.54 g/m^3 throughout the year 2018 as indicated in Figure 3. Furthermore, it is worth noting that in the year 2018, the region of Mamelodi had heightened levels of PM_{10}, with concentrations peaking at a notable 67.37 g/m^3. In 2019, the area of Booysens had elevated concentrations of PM_{10}, with recorded readings peaking at 60.31 g/m^3. When comparing Booysens with Olievenhoutbosch, it was observed that Olievenhoutbosch had elevated levels of PM_{10} concentration, with a peak value of 124.2 g/m^3 recorded throughout the 2019 season. Additionally, it is noteworthy that Rosslyn had a substantial rise in PM_{10} concentration levels, reaching a value of 54.61 g/m^3 in the year 2019. Furthermore, an analysis was conducted on the levels of PM_{10} concentration in the region of Mamelodi, resulting in a recorded measurement of 206.63 g/m^3 throughout the year 2020. It is essential to acknowledge that the recorded PM_{10} concentrations in Rosslyn amounted to 39.76 g/m^3.

According to WHO, 2022, the sources of air pollution in African cities include industrial sources, emissions from dwellings, and vehicles, amongst other things. Similarly, the City of Tshwane is one of the capital cities of South Africa; therefore, it is regarded as the economic hub where there is a lot of traffic to and from the city. As a result, a high concentration of PM_{10} might be emanating from the increased traffic volume of cars. This observation is similar to the discoveries recorded by Ndletyana et al. (2023), where it was discovered that elevated concentrations of PM_{10} were found close to national highways and traffic intersections in the Central Business District in Cape Town.

Among other factors, one of the primary contributors to air pollution is the rise in car ownership and individual utilization for transportation purposes within African cities and metropolitan regions. This method conveniently facilitates the production of intricate combinations of air contaminants that adversely affect human health. More precisely, they affect the emission of harmful particulate matter (PM) and NO_2 levels. Similarly, previous studies have revealed that both pollutants are linked to an escalation in the prevalence of illness and the worsening of pre-existing health disorders (Bowe et al., 2017; Strak et al., 2021). Therefore, given the greater risk of the burden of disease associated with these pollutants, their epidemiological effects monitoring is of paramount importance for the vulnerable population of Sub-Saharan Africa. These would provide the relevant data that is fundamentally needed to inform air quality management policy and, in the process, minimize the extrapolation of epidemiological effects data that disregards the social vulnerability.

Seasonal exposure variation of NO_2 in all the stations

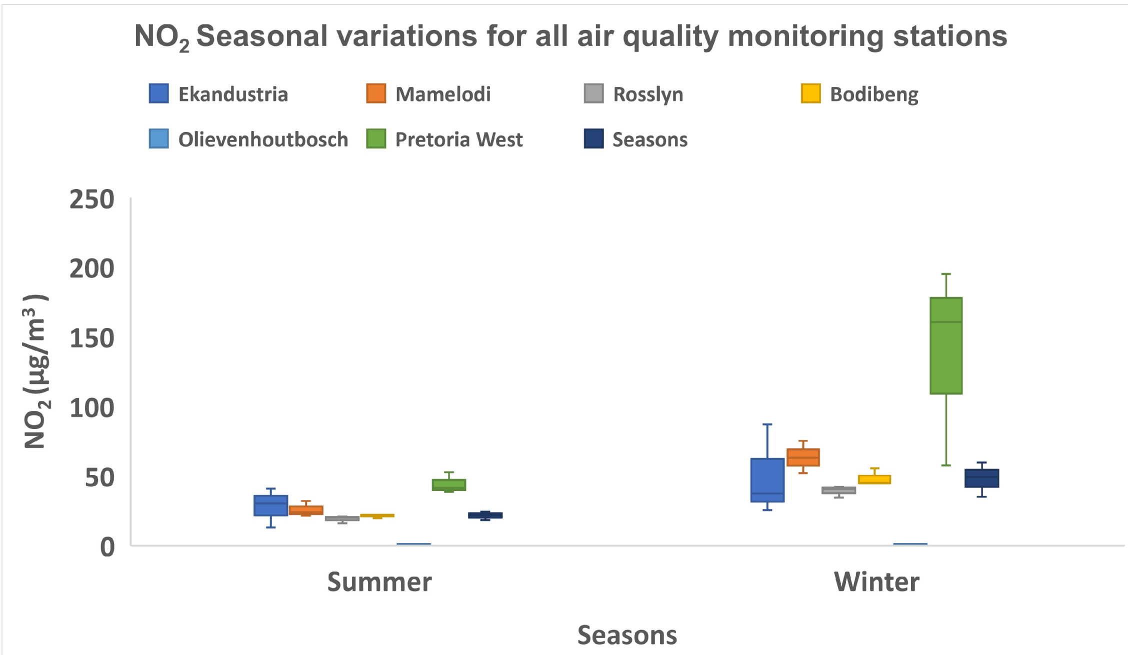

Figure 4: Mean annual concentration of NO_2 during summer and winter months in the study areas of Tshwane.

Figure 4 illustrates distinct seasonal variations in pollution levels, wherein the winter months exhibit the greatest concentrations while the summer months demonstrate the lowest levels across all monitoring locations examined in the study. The box and whisker plots illustrate the fluctuations in levels of pollutant exposure across many locations, with a particular focus on the disparities seen throughout different seasons. The findings suggest that there has been a seasonal variation in the amounts of NO_2 observed at all monitoring locations between the years 2016 and 2020. According to figure 4 the concentrations of Ekandustria exhibited fluctuations ranging from 12.85 to 40.85 g/m^3 over the summer period, as visually depicted. During the winter season, however, concentrations exhibited variations ranging from 37.42 to 87.22 g/m^3 throughout the course of the years. Moreover, in comparison to Ekandustria, the Mamelodi monitoring station observed a variety of NO_2 values ranging from 21.44 to 31.91 g/m^3 during non-winter months. Conversely, the range escalated from 52.31 to 75.41 g/m^3 during the winter season. Additionally, it is worth noting that nitrogen dioxide concentrations exhibited a range of 19.71 to 21.96 g/m^3 throughout the summer season. Conversely, in the winter season, there was a substantial increase in pollutant concentrations, with a range of 44.7 to 55.78 g/m^3 as indicated in figure 4, representing a twofold rise. Furthermore, the concentrations of NO_2 in Pretoria West exhibited a range of 38.35 to 52.92 g/m^3 during the summer season. However, this range increased significantly to between 57.85 and 195.02 g/m^3 during the winter season. In the summer season, the NO_2 concentrations in Booysens were seen to fall within the range of 18.25 to 24.35 g/m^3 (figure 4). Whereas, during the winter season, the concentrations exhibited a wider range, varying from 34.93 to 59.77 g/m^3. In the selected research area, there is a progressive increase in NO_2 concentrations from the summer season to the winter season. During the winter season, there was a substantial rise in the levels of NO_2 pollution.

This study's results resemble prior research carried out in the core business centre of Cape Town. The study conducted by Ndletyana et al. (2023) found a significant rise in NO_2 levels in the winter, whereas, lower concentrations were detected during the summer months. This observation demonstrates that the transition between seasons significantly impacts the rise in air pollution levels. The heightened levels of exposure that have been recorded are likely to be affected by the land-use practices that are now prevalent. Multiple factors contribute to the occurrence of air pollution, including the burning of wood and biomass as well as the release of pollutants from motor operations, particularly in the monitoring stations of Booysens and PTA West. These regions are notable for their industrial presence and informal settlements, further exacerbating the problem. The studies by Bouchlaghem and Nsom (2012), Laakso et al. (2012), Mentz et al. (2018), and Muttoo et al. (2018) found that elevated NO_2 concentrations during the winter season can be attributed to higher heating demands, decreased photochemical activities, and reduced atmospheric mixing.

Furthermore, the levels of NO_2 throughout both the summer and winter seasons are subject to substantial effects from an intensified oxidation process. This process involves decreased photochemical interactions between NO_2 and hydroxyl (OH) radicals, forming nitric acid (HNO_3). Several ambient air quality monitoring studies have also observed this pattern (Nguyen et al., 2006; Al Katheeri et al., 2012).

Seasonal exposure variation of PM_{10} in all the stations.

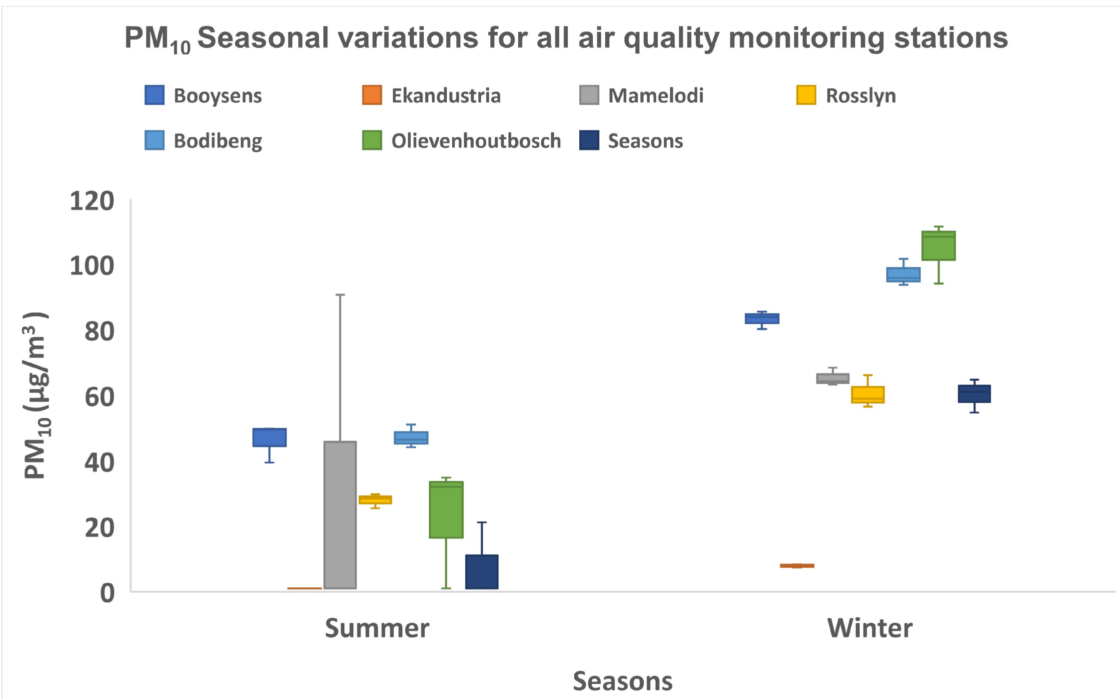

Figure 5: Mean seasonal concentrations of PM_{10} for all stations.

Figure 5 depicts the mean seasonal levels of PM_{10} ascertained during the summer and winter seasons. Box and Whisker plots visually represent the range and distribution of pollutant exposure data across different seasons. These differences were shown to exist across several other locations. Based on the findings shown in Figure 5, it can be observed that Booysens experienced PM_{10} concentration levels ranging from 39.53 to 49.91 µg/m^3 during the summer season. In contrast, the aforementioned values exhibited a rise to a range of 80.27 to 85.53 µg/m^3 over the winter season. The Mamelodi monitoring station observed a diverse range of PM_{10} values, spanning from 1 to 90.74 µg/m^3, over the summer season. In the winter season, the measured values of PM_{10} ranged from 63.30 to 68.49 µg/m^3. In addition, Rosslyn recorded PM_{10} values within the range of 25.49 to 28.38 µg/m^3 during the summer season, whereas during the winter season, the range expanded to 59.02 and 66.14 µg/m^3. Furthermore, it was noted that the concentration levels in Bodibeng fell within the range of 44.22 to 51.06 µg/m^3 throughout the summer season. Conversely, in the winter season, the PM_{10} concentrations exhibited variability, ranging from 93.70 to 101.67 µg/m^3. In a similar vein, the Olievenhoutbosch area documented PM_{10} concentration values that varied from 1 to 31.96 µg/m^3 in the summer season, and from 94.13 to 111.65 µg/m^3 in the winter season. The results of this inquiry align with a prior analysis carried out in Rome, wherein it was noted that the levels of PM_{10} were notably higher during the colder season in comparison to the warmer season (Bodor et al., 2020). Whereas, the research conducted by Bodor et al. (2020), provided evidence supporting the significant seasonal variations in

PM_{10} levels. The study revealed that the highest concentrations of PM_{10} were consistently seen throughout the winter months, while the lowest levels were consistently recorded during the summer. Furthermore, the findings are consistent with the claims put out by Laid et al. (2006) on the average PM_{10} concentrations in Algiers. Specifically, they reported that the mean PM_{10} levels during the winter season were higher (74 ± 35 µg/m^3) compared to the summer season (48 ± 21 µg/m^3). Additionally, this discovery is consistent with the investigation carried out by Moja (2019) in the City of Tshwane, where heightened concentrations of PM_{10} were discovered throughout the winter months and reduced levels were recorded during the summer months.

Independent-sample t-test comparing seasons

Table 1. Independent-samples t-test comparing seasons

	N	Mean	Std. Deviation	Std. Error Mean
NO₂				
Summer	33344	10.6709	12.65260	0.06929
Winter	32354	25.8248	36.20045	0.20126
PM₁₀				
Summer	17124	43.8076	77.48116	0.59210
Winter	24466	77.7849	95.52787	0.61073

Table 1 shows each group's mean and standard deviation (summer/winter). It also shows the number of air quality data in each group (N).

The independent-sample t-test is a tool used to test whether there are significant differences in the mean scores on the dependent variable (continuous variables) for two seasons (Summer and winter). The independent-sample t-test, comparing seasons for created continuous variables, is summarized in Table 1 above.

Levene's test for homogeneity of variances was employed to examine whether there is an equal amount of variation in scores between the two independent groups, namely summer and winter. The determination of the t-value to employ is based on the outcome of Levene's test. If the p-values obtained from Levene's test are greater than 0.05, it can be concluded that the homogeneity of variance assumptions were not violated. Therefore, the premise of equal variances should be understood. Nevertheless, when the significance threshold is equal to or less than p=0.05, it indicates that the variances of the two groups (summer and winter) are statistically different. Hence, the assumption of unequal variances should be employed to account for the presence of non-identical variances.

Table 2: Independent-samples t-test seasonal variations

	Levene's Test for Equality of Variances		t-test for Equality of Means			
Independent t-test	F	Sig.	T	df	p-value	Mean Difference
NO₂						
Equal variances assumed	5144.598	0.000	-72.039	65696	0.000	-15.15389
Equal variances are not assumed.			-71.195	39933.000	0.000	-15.15389
PM₁₀						
Equal variances assumed	827.096	<,001	-38.514	41588	0.000	-33.97735
Equal variances are not assumed.			-39.944	40697.848	0.000	-33.97735

Table 2 above shows a significant difference between the means of NO_2 and PM_{10} for the two independent groups (season).

Table 2 shows that Levene's test significance level types of NO_2 and PM_{10} are 0.000 and 0.000, respectively. The results of the independent-samples t-test indicate that there is a statistically significant difference between the groups in terms of NO_2, the average score during the summer (M = 10.6709, SD = 12.65260) exhibited a statistically significant decrease compared to the average score during the winter (M = 25.8248, SD = 36.20045), t (39933.000) = -71.195, p=0.000. Additionally, the analysis of PM_{10} data reveals that the average score during the summer season (M = 43.8076, SD = 77.48116) was considerably lower compared to the average score during the winter season (M = 95.52787, SD = 95.52787), t (40697.848) = -39.944, p=0.000. Therefore, this means that the variances of the two groups (summer and winter) are statistically different.

Compliance of Tshwane's exposure concentrations with NAAQS exposure levels for PM_{10} and NO_2

Table 3: South African Air Quality Standards

Air quality standards for Nitrogen Dioxide		
1 year	40 µg/m^3	DEA (2009)
Air quality standards for particulate matter		
1 year	40 µg/m^3	DEA (2009)

Table 3 above shows the air quality standards for nitrogen dioxide and particulate matter in South Africa.

The monitoring data from the seven monitoring sites was assessed to facilitate a comparison with the national ambient air quality standard, as shown in Table 3 below. The establishment of ambient air quality standards plays a crucial role in managing air quality from a policy perspective. Implementing the National Ambient Air Quality Standards (NAAQS) in South Africa marked a significant change in the approach to air quality management, shifting the emphasis from source-oriented to receptor-oriented strategies. This transition was initially set in motion with the passage of the National Environmental Management: Air Quality Act (NEM: AQA). The development of the National Ambient Air Quality Standards (NAAQS) took several factors into account, including the potential health implications, prevailing ambient levels, and the economic growth of South Africa. The study findings are reported for the three primary pollutants that are of significant importance in South Africa, specifically Nitrogen dioxide, and particulate matter (Thompson et al., 2011; Lourens et al., 2011; Venter et al., 2012).

Compliance of Tshwane's exposure concentrations with NAAQS exposure levels for NO_2

According to Table 1, the findings suggest that the levels of NO_2 concentrations in the monitoring stations of Bodibeng, Ekandustria, and Olievenhoutbosch were all below the established threshold value of 40 µg/m^3. The recorded values ranged from 10.41 µg/m^3 to a maximum of 39.79 µg/m^3. Nevertheless, it was observed that the concentration in Mamelodi was above the designated limit amount, measuring 50.9 µg/m^3 in 2019. Comparably, monitoring stations such as Booysens recorded concentrations of 60 and 51.37 µg/m^3 as shown in figure 2, in the years 2016 and 2020, correspondingly. Rosslyn recorded a concentration of 43.35 µg/m^3 in 2016. Notably, Pretoria West experienced a doubling of the exceedance, reaching a concentration of 80.75 µg/m^3. This finding resembles a previous investigation conducted in Libya, where the concentration of NO_2 surpassed the allowable thresholds, particularly in the vicinity of industrial zones such as electricity generation and cement manufacturing, as documented by Nassar et al. (2017). It is essential to highlight that all these recorded values exceeded the established air quality limits. Due to the proximity of these monitoring sites to roadways, it is possible that emissions from motor vehicles were the cause of the elevated levels of NO_2 concentration. In and around the Tshwane central business area, there is heavy automobile traffic early in the morning and late in the evening throughout the weekdays. Biomass burning, the combustion of fossil fuels, and transportation are some of the most significant human-caused contributors to NO_2 levels in the atmosphere (Georgoulias et al. 2019; He et al. 2019; Qin et al. 2020; Wang and Su 2020; Lerma et al. 2021).

Nitrogen dioxide (NO_2) is a pollutant with a very short lifespan, as evidenced by studies conducted by Marchenko et al. (2015) and Lamsal et al. (2020). It is particularly prevalent in urban settings, as indicated by the research undertaken by Georgoulias et al. (2019) and Otmani et al. (2020). NO_2 exhibits detrimental effects on the environment and human health, particularly when individuals are exposed to it for extended periods (Manisalidis et al., 2020; Otmani et al., 2020). Several adverse effects on human health have been identified, such as respiratory ailments, coughing, and wheezing, which can be attributed to the ability of NO_2 to infiltrate and erode the inner regions of the lungs (Manisalidis et al., 2020; Wang & Su, 2020). In addition, NO_2 is known to produce nitric acid, nitrate aerosols, and peroxyacetyl nitrate (HNO_3) (Lamsal et al., 2020; Wang and Su, 2020). These compounds adversely affect agricultural yields (Manisalidis et al., 2020) and the environment. NO_2 and nitric oxide (NO), collectively known as nitrogen oxides, play a crucial role in the photochemical reactions involving ozone (O_3) in both the stratosphere and troposphere (Grajales and Baquero-Bernal, 2014; Lamsal et al., 2020; Qin et al., 2020) thus, could lead to global warming (Lary, 2004; Itoba-Tombo et al., 2017) These reactions occur under the influence of solar radiation (Lerma et al., 2021).

Compliance of Tshwane's exposure concentrations with NAAQS exposure levels for PM_{10}

The results indicate that the concentrations of PM_{10} in Figure 3 exceeded the prescribed air quality threshold at Ekandustria and Pretoria West, with recorded measurements of 6.77 and 24.28 µg/m^3, respectively, as presented in Table 3. However, the prescribed limit was exceeded in several stations. Bodibeng, for instance, recorded PM_{10} concentrations of 49.21, 62.55, and 78.18 µg/m^3 in 2016, 2017, and 2018, respectively. Similarly, Booysens recorded 61.99 and 60.31 µg/m^3 concentrations in 2017 and 2019, respectively. Olievenhoutbosch recorded a concentration of 124.4 µg/m^3 in 2019, while Mamelodi recorded a concentration of 206.63 µg/m^3 in 2020. Lastly, Rosslyn recorded a concentration of 500.58 µg/m^3 in 2017. The above stations are in regions characterized by industrial establishments, formal and informal residential settlements, and high-traffic road networks. Consequently, it is possible that the observed heightened levels of PM_{10} could be attributed to many sources, such as industrial operations, transportation, residential activities involving biomass burning, and the suspension of dust particles. In addition, residential fuel sources such as coal, wood, and paraffin are commonly utilized for cooking and heating purposes in lower-class households and informal settlements in South Africa (Koppman et al., 2011). Therefore, the reliance on such fuel sources can be attributed to the absence of more affordable or readily available alternatives. Moreover, the Tshwane region is characterized by a substantial informal settlement, making it one of the largest in Gauteng. Consequently, the prevalence of pollution stemming from household fuel burning is notably greater in this area (DEA, 2010).

Additionally, the spatial and temporal variations in PM_{10} concentration levels are influenced by various factors, including meteorological conditions and human activities. These activities include emissions from vehicles, households, and industries. This variability has been observed throughout different provinces in South Africa, as shown by Mkoma et al. (2011) and Czernecki (2017). Furthermore, PM_{10} is considered the best indicator of ambient air pollution health effects (Burnett et al., 2014; WHO, 2014). Many human activities contributing to ambient PM_{10} also contribute to climate change and other health impacts (Karagulian et al., 2014). Understanding the sources and activities contributing to local ambient air pollution levels is vital to reduce exposure to air pollution and the associated health impacts. For this reason, a growing number of regional studies focus on the contribution of sources to air pollution levels, most often at the town level. Such studies consider several pollution sources, such as industrial actions, transport, biomass burning/residential activities, re-suspended dust, sea salt and different unspecified pollution sources of human origin (Karagulian et al., 2014).

The emission of particulate matter can have a variety of detrimental consequences on human wellness, both in the short term and the long term, such as a rise in the number of health problems (Chang, Peng, and Dominici, 2011; Cassee et al., 2013; Beltrando, 2014; Li and et al., 2018; Chen et al., 2019).

Conclusion

The findings of the study indicated that the mean levels of NO_2 and PM_{10} concentrations are above the required thresholds set by the National Ambient Air Quality Standards (NAAQS) in many regions during a span of five years. Additionally, these findings indicate that the levels of air pollution in the City of Tshwane Municipality, specifically in relation to NO_2 and PM_{10}, are significant and may have significant ramifications for public health and the environment. The examination of pollutant distribution patterns within the research demonstrates fluctuations in concentration influenced by geographical and temporal variables. The observed discrepancies occur as a result of the specific activities carried out at a given location, including factors such as significant levels of traffic, the practice of open incineration, and emissions originating from industrial sources.

The research sites displayed differences in seasonal characteristics, particularly during the summer and winter seasons. Based on the results, it was seen that there were increased levels of NO_2 and PM_{10} during the winter season, whereas reduced levels were observed during the summer season. Moreover, it may be inferred that the magnitude of air emissions in a given geographical area is influenced by seasonal fluctuations.

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